Operation and Maintenance of the Wasatch Front, Utah, GPS Network (Monitoring, Upgrades, Data Recording and Processing)

Operated as part of the University of Utah EBRY (Eastern Basin Range-Yellowstone) GPS Network

Annual Report for Period
October 1, 2003 to September 30, 2004

USGS Award Number 04HQAG0023

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Program Element: Intermountain (regional earthquake hazards assessments, research on earthquake occurrence, physics and effects)

Key Words: GPS-Continuous, Regional Seismic Hazards, Elastic Fault Modeling, Earthquake Effects

I. Investigations Undertaken Summary

Under this USGS National Earthquake Hazard Program project, the University of Utah conducted research focused on continuously operating the Wasatch Front GPS network to monitor the surface deformation of the populated Wasatch Front area, Utah. High resolution GPS data, acquired by 20 continuous stations and seven field campaign surveys of ~ 60 stations, were integrated with other earthquake source data, including paleoearthquake fault-slip rates and historic seismicity, to evaluate the earthquake hazard of the Wasatch fault.

Continuous and Campaign GPS Observations -- Our main field project included the operation and maintenance of seven University of Utah continuous GPS stations, of which a new monument at Hardware Ranch, Utah (HWUT) was installed in the summer of 2004 (Figure 1). Our CGPS data are sent daily to the UNAVCO archive center and are web accessible to any user in near-real time (http://archive.unavco.org/query/pss). Moreover, we conducted a GPS campaign field survey along the central and southern Wasatch fault in 2003 where the data were processed together with six previous GPS campaigns to update the contemporary velocity field. Our results indicate that the Wasatch Front area has notably higher ground deformation than expected from geologic data and is interpreted to relate to fault-loading processes of the Wasatch fault and surrounding structures. This increases the earthquake hazard from previous estimates.

Data Processing -- We also finished developing automatic GPS data processing of total 20 stations in the north and central area of Utah, encompassing the Wasatch fault, that include seven from the University of Utah, five from the BARGEN CGPS array, three from the EarthScope PBO network, and five from other cooperative CORS stations (Continuously Operating Reference Station of the Nation Geodetic Survey (NGS)). Our processing schema uses precise (final) GPS orbit data acquired from International GPS Service (IGS), which are available at a 12-day latency. With this scheme the Wasatch fault GPS time-series are automatically updated weekly using the past two weeks precise orbit data. The resulting processes GPS data are posted on our website at http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html.

Contemporary Loading Rates of Wasatch Fault from GPS Data -- We used the resulting GPS data to determine the contemporary crustal loading rates of the Wasatch Front area based on the derived horizontal velocity field. We then employed an elastic dual-dislocation fault simulation to estimate the fault-loading rates and related elastic parameters. This model assumes loading of the fault is taking place beneath the locked-upper crust containing the elastic controlled Wasatch fault, or at depths beneath the seismic locking depth of ~10 km. Our results show that the loading rates are 5-6 mm/yr on a west-dipping, ~30°, creeping zone that is about a factor of 2 to 3 higher than the geological fault-slip rate of the Wasatch at the surface. The high loading rate of this system, if assuming all of the stress is concentrated on the seismogenic fault, implies a higher earthquake ground-shaking hazard from the fault compared with that calculated only by historic seismicity and paleoearthquake data.

Integrated Earthquake Hazard -- Various earthquake sources and recurrence models contribute differently to the probabilistic earthquake hazard estimations. The Wasatch Front seismic, geologic, paleoearthquake, and GPS data were included in a study to evaluate the probabilistic ground-shaking hazard for a specific location in Salt Lake Valley. Results demonstrate the usefulness of integrating all available data for a more complete estimate of earthquake hazard for the entire region.

II. Results (October 1, 2003 to September 30, 2004)

General Accomplishments -- Under this project, the University of Utah received support to assess earthquake hazard on the Wasatch Front, Utah using continous and campaign high precision GPS measurements and investigating inter-seismic models of normal fault behavior applied to the Wasatch fault. Because of reduced funding from our initially proposed project, tasks were reduced to four elements: 1) Building and installing one new continuous-GPS (CGPS) sites in the northern Wasatch fault, maintenance of six CGPS sites on the Wasatch Front, and incorporating CGPS data from five stations of BARGEN northern Basin-Range array, three of the newly installed EarthScope PBO stations in northwestern Utah, and five sites recorded as part of the CORS network. This provides a total of 20 continuous GPS stations in our processing scheme; 2) Conducting a GPS campaign survey during the summer-autumn of 2003 of 29 sites covering the central and southern Wasatch fault (Salt Lake City and Provo segments), which extends the time span of the Wasatch campaigns (started in 1992) up to 11 years; 3) Estimating the loading rate of the Wasatch fault based on the horizontal velocity field from GPS data using a dual-dislocation fault model to best simulate the hypothesized three-dimensional Wasatch fault geometry; and 4) Evaluating the contributions of various seismic sources and fault scenarios to the probabilistic ground-shaking hazard for a specific location in Salt Lake Valley. These incorporated the Wasatch fault seismic, geologic, paleoearthquake, and GPS observations

In addition, Dr. WuLung Chang also completed a Ph.D. dissertation focused on a study of the Wasatch fault behaviors and related earthquake hazards using GPS observations.

Specific efforts included:

- Operating and maintaining seven permanent GPS stations, of which a new station HWUT at the Hardware Ranch, Utah was installed in the summer of 2004 (Figure 1). Note that this site is located on the footwall of the Wasatch fault and can form baselines with hanging-wall CGPS stations to study the interseismic behavior of the northern Wasatch fault (the Brigham City segment) that has the longest elapsed time (~2,100 yr B.P.).

- Note that the HWUT site is a cooperative USGS-University of Utah site with a co-located USGS ANSS seismograph station. The GPS data are telemetered via the USGS VSAT system to Golden, Colorado and then retransmitted to the Univ. of Utah. This telemetry scheme notably reduces the operational costs of the site.

- We have worked diligently to add another GPS station in the immediate vicinity of the Wasatch fault footwall-block near Salt Lake City to assist with monitoring ground motions along this most populated part of the Wasatch Front. For this task we sought a special use permit for a new CGPS station in Albion Basin at Alta Utah. The Alta Ski Lift Corporation has now gave us provisional permission to install a GPS site on one of their unused 20' steel towers erected on bedrock. This site, designated ALUT (Figure 1), will have solar power and transmit data in real-time to a University of Utah seismic station at the Alta town office. This station will be installed in spring 2005, now that we have 75" of snow on the ground at the proposed site.

- A major GPS campaign survey, consisting of 29 sites, was conducted during the summer-autumn of 2003 covering the central and southern Wasatch fault (Salt Lake City and Provo segments), which extends the time span of the Wasatch campaigns (started in 1992) up to 11 years. This longer time interval especially increases the quality of the estimated velocities in the southern Wasatch fault area by a factor of 1.5 compared with our previous 1994-1999 results.

- These surveys were materially enhanced by the contribution, at little cost to the project, by the use of four GPS receivers and trained undergraduate students under the supervision of Professor Ron Harris of Brigham Young University.

- Automatic processing data was routinely done for 34 CGPS stations in the Intermountain region, including 20 in the Wasatch Front and 14 around the Yellowstone-Snake River Plain area. Updated time series of these stations are posted on our website: http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html.

- Daily downloads of our CGPS data are sent to the UNAVCO data archive for web access to any interested user at http://archive.unavco.org/query/pss.

- University of Utah GPS data, including the Wasatch fault array, are described along with processed time series and relative crustal motion vectors on our website http://www.mines.utah.edu/~rbsmith/RESEARCH/UUGPS.html

- Modeling the GPS data was investigated using linear and non-linear inverse methods to determine the geometry and rates of causative faults especially incorporating the 3D geometry of the Wasatch fault.

- Continued development of a Wasatch Front time-dependent earthquake hazard model by integrating GPS observations into the probabilistic ground-shaking hazard analysis.

- Presented invited and contributed papers on our research at the following scientific meetings: 1) the 2003 Fall Meetings of the American Geophysical Union; 2) the 2004 Basin and Range Seismic Hazards Summit II of the Western States Seismic Policy Council, and 3) lead convener and presentation give on earthquake hazards of the Basin-Range at the September, 2004, SESAC meetings, Jackson, Wyoming, attended by USGS Director Chip Groat and Asst. Secr. of Interior, Bennett Raley.

- Organized an effort to include the northern Basin-Range, adjacent to the Wasatch fault, as a major element of the Plate Boundary Observatory. This component will provide three profiles of CGPS stations extending west from the Wasatch fault at ~15 km intervals complimentary to our USGS funded stations. The research objective is to focus on the physics of earthquakes as well as an example of GPS monitoring of an active fault with major societal impact.

Wasatch Front Continuous GPS (CGPS) Operation

The Wasatch Front CGPS network has been operating for nearly seven years (1997-present). Our seven continuous GPS sites (Figure 1) are designed to operate in high mountainous, cold weather environment planned for reliable unattended operation. The instrumentation includes photovoltaic power (except for Lake Mountain) and digital spread-spectrum radios for RF telemetry between the sites and the University of Utah GPS recording laboratory. Monuments consist of choke-ring antennas are attached to 2-inch stainless steel rods set in 3-4 foot long boreholes drilled into bedrock. Four of original stations (RBUT, NAIU, LMUT, and EOUT) are equipped with Trimble SSI dual-frequency GPS receivers (*acquired at no cost to the project by a grant to the University of Utah from the National Science Foundation*), and three new stations (MPUT, LTUT, and HWUT) use Ashtech Micro Z dual frequency receivers.

Spread spectrum digital radio links to the University of Utah campus transmit the GPS data which are then recorded on a Sun UltraSparc computer. Data are sampled at a 30-second rate.

Automatic processing of the Wasatch Front CGPS data uses the Bernese Processing Engine of the new Bernese 4.2 software. Our automatic data processing scheme uses the precise (final) GPS orbit data from NGS that are available weekly with a two-week delay. The time series of the total 34 CGPS stations (including 14 of the Yellowstone-Snake River Plain network) are thus updated every week to the past two weeks and posted on the website: http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html.

Coordinate solutions are saved in SINEX-formatted files that can rigorously be combined with solutions determined by other institutions using different processing software.

The reconnaissance and initial permitting of a new CGPS monument at the Alta Ski Resort (ALUT) east of the Wasatch fault was accomplished. This site will provide key data on the footwall of the Salt Lake City segment of the Wasatch fault. We specifically note that because of logistical problems and early winter, we were unable to install this station in 2004, and plan on installing it in 2005.

Problems Encountered -- No major logistical problems were encountered during the report period except the extended negotiations of permitting the Alta site due to strict environmental requirements and engineering specifications required by the ski corporation.

2003 Wasatch Front Campaign GPS Survey

GPS campaign survey provides denser and broader station spacing and materially add new information to the 3-D velocity field obtained by CGPS. During the summer and fall of 2003, the University of Utah, in cooperation with Brigham Young University, conducted a GPS field campaign along the central and southern Wasatch fault. We had re-occupied 29 sites whose baselines cross the Salt Lake City, Provo, and Nephi segments of the fault.

The above data were jointly processed with that from previous Wasatch campaigns (1992, 1993, 1994, 1995, 1999, and 2001) using the new Bernese 4.2 software. With time span up to 11 years, we expect to get more evident deformation rate with lower error on most of the stations. These results will provide necessary data for kinematic analyses of the Wasatch fault, as well as contemporary information on its aseismic nature as input of its earthquake hazard assessments.

III. Research Results

During the report period we evaluated various processing schemes to incorporate the best reference frame. Multi level tests of updated reference for our non-uniform 2-D velocity field with respect to the stable North America reference frame was best employed by ITRF2000, International Terrestrial Reference Frame 2000 (Figure 2).

Processing all of our data, from the begging of our GPS studies in 1995, in this framework revealed that strain is negligible east of the Wasatch fault, but increases rapidly west of the fault to a principal component of E-W extensional strain at ~ 0.028 ± 0.008 μstrain/yr, corresponding to a velocity of 1.8 ± 0.5 mm/yr a 65-km wide area spanning the fault. This rate is comparable to that from the earlier campaign surveys, that showed a regional horizontal strain rate of 0.049 ± 0.023 μstrain/yr corresponding to a velocity of 2.7 ± 1.3 mm/yr across 55-km wide area spanning the Wasatch fault (Martinez et al., 1998). Baselines that cross the fault also show an increase of strain from south to north, corresponding to a change of 1.8 to 2.6 mm/yr. These spatial variations imply that local tectonic strain is heterogeneous in both NS and EW directions.

Compared with the velocity field derived from the previous GPS campaigns (blue arrows in Figure 2), results including the new 2003 campaign data reveal consistent velocity field in most of the network (green arrows in Figure 2) except some stations adjacent to the Provo segment that show opposite motions. This temporal variation of ground motion may be caused by non-tectonic signals (e.g. change of groundwater table or monument instability), but further studies are needed to resolve this observation.

Elastic Modeling for Fault Geometry Using GPS Measurements

Using the horizontal deformation results from the CGPS and the campaign GPS surveys, we ran various tests of nonlinear inversions on fault geometry and loading rates. Before doing this, we first estimated and removed the background tectonic motion, namely the extension of the eastern Basin and Range from our observed velocities, to obtain the motion caused only by the loading of the Wasatch fault. Moreover, the fault length was fixed to 350 km, the total length of the geologically mapped Wasatch fault that is long enough to avoid the dislocation edge effect. Results for the Wasatch fault suggest a best fit to the GPS data by a fault plane with a width of 23 km, a strike of N4ºW, a dip of 27º beneath a seismogenic zone beginning at a locking depth of 9 km, and with a fault loading rate of 7 mm/yr (Figure 3) that is notably higher than the rate derived from the paleoseismic data (~ 1-2 mm/yr).

The prominent change in azimuth of the surface trace of ~ 30º, the Wasatch fault at the Provo segment (Figure 4), on the other hand, can be a factor affecting the deformation field. Despite the values of using a simple, single-dislocation model, such as reducing unknown fault parameters thus the inversion errors, dual-dislocation fault model are examined in our study to offer a better and geologically more plausible fit to the GPS data.

Two different on strike-dislocations were employed with uniform dip-slip displacements as a working model for the interseismic loading (creeping) part of the Wasatch fault. With constrains based on L. Quaternary slip rates from trenching and multi-segment fault models, the optimal dual-dislocation model that best fits the GPS-observed horizontal velocity vectors is shown in Figure 4.

These results show that the loading rates are 5 and 6 mm/yr for the northern and southern Wasatch fault, respectively, that are about a factor of 2 to 3 higher than the geological fault-slip rate. Note that the dual-dislocation model implies higher west velocities near the fault scarp, which fits the observations better than the model with single fault patch. The improved results of using two fault segments to model the Wasatch Front horizontal velocity field suggest that multi-dislocation models with geometry similar to the fault surface traces may be plausible to describe the interseismic behavior of the Wasatch fault.

Ground-Shaking Hazard Estimation

Our study also represents an example of an integrated probabilistic earthquake ground-shaking hazard estimation incorporating seismic, geologic, and geodetic data of the Wasatch Front area. We calculated the hazard values for a single point in the center of the Salt Lake Valley, at the intersection of interstate highways, I-15 and I-80 that is a good approximation for hazard within the populated cities on the alluvial-filled valley of the Wasatch Front to demonstrate our ideas.

Figure 5 shows the ground-shaking hazard curves, or the annual frequency of exceedance of horizontal peak ground acceleration (HPGA). Compared with the historic-seismicity hazard curve (gray curve), which is considered to be the lower bound, including the paleoearthquake occurrence and geodetic moment rates increases the annual frequency of PGA ≥ 0.25g by a factor of 1.7. The upper-bound scenarios considering geodetic fault-loading rate and fault-stress loading effect that takes into account the change of probability of the adjacent fault rupture caused by the loading (or unloading) of the failure stress. Moreover, increase the annual frequency of PGA ≥ 0.7g by a factor of about 3.0. These results demonstrate the usefulness of integrating all available data for a more complete estimate of earthquake hazard for the entire region.

IV. Non-Technical Summary

Under the USGS National Earthquake Hazard Program, the University of Utah conducted research focused on evaluating earthquake hazards of the Wasatch Front, Utah and by operating the Wasatch Front GPS (Global Positioning Systems) network to monitor the surface deformation of the populated Wasatch Front area, Utah. High resolution GPS data, acquired by 20 continuous stations and seven field campaign surveys of ~ 60 stations, were integrated with other earthquake source data, including paleoearthquake fault-slip rates and historic seismicity, to evaluate the earthquake hazard of the Wasatch fault. Our results suggest that the Wasatch Front area has notably higher ground deformation rates than expected from the Quaternary fault data and is interpreted to relate to fault-loading processes of the Wasatch fault and surrounding structures. This increases the earthquake hazard from previous estimates. The University of Utah GPS data of seven stations are automatically sent to the University Navigation Consortium (UNAVCO) archive on a daily basis and accessible to any user over the Internet in near-real time and our research results are provided to any user via the web.

V. Meeting Participations – We presented invited and contributed papers on our research at the: 1) the 2003 Fall Meetings of the American Geophysical Union; and 2) the 2004 Basin and Range Seismic Hazards Summit II of the Western States Seismic Policy Council.

VI Collaborative Efforts – We continue to work with Professor Ron Harris of Brigham Young University, Provo Utah for campaign GPS measurements. Dr. Harris has four Trimble GPS receivers that he loans to us when needed. Moreover, he supervises a team of undergraduate students that conduct campaign GPS surveys of the Wasatch fault in 2003 to our specifications costing us only their salaries and travel. This cooperative effort has materially contributed to this project.

VII. Papers, Presentations, Dissertations, etc. Related To Project (2003-2004)

Dissertation Completed With Primary Support of Project. (2003-2004)

Chang, W. L., 2004, GPS studies of the Wasatch fault zone, Utah, with implications from elastic and viscoelastic fault behavior and earthquake hazard, *Ph.D. Dissertation*, University of Utah, Salt Lake City, 201 pp.

Papers, and Presentations Related To Project (2002-2004)

Chang, W. L. and R. B. Smith, 2002, Integrated seismic-hazard analysis of the Wasatch Front, Utah, *Bull. Seismol. Soc. Am.* **92**, 1904-1922.

Chang, W. L., R. B. Smith, and C. M. Puskas, 2003, Rheology of Extending Lithosphere From Postseismic Deformation of Large Basin-Range Normal-Faulting Earthquakes, *Eos. Trans. AGU* **84**, F1033.

Chang, W. L. and R. B. Smith, 2004, Integrated earthquake hazard of the Wasatch Front from GPS measurements ad elastic-viscoelastic fault modeling, *Programs and Abstracts, Basin and Range Province Seismic Hazards Summit II, Western States Seismic Policy Council*, 73-76.

Meertens, C.M., R.B. Smith, C. Puskas, and W. Chang, 2002, Contemporary deformation of the Yellowstone caldera from GPS, *Abs. Program, 1st Annual Science Workshop, Yellowstone Volcano Observatory*, April 4, Salt Lake City, Utah.

Smith, R. B., 2004, Earthquake Hazards of the Eastern Basin-Range Province, presented at the September 2004 SESAC (Scientific Earthquake Studies Advisory Committee of the USGS) meetings, Jackson, Wyoming.

Youngs, R, W. Arabasz, W., W. Anderson, A. Ramelli, J. Ake, D. Slemmons, J.P. McCalpin, D. I. Doser, C. J. Fridrich, F. Swan III, A. Rogers, J. Yount, L. Anderson, K. Smith, R. Smith and Ronald L. Bruhn, 2003, A methodology for probabilistic fault displacement hazard analysis (PFDHA), *Earthquake Spectra*, **19**, Issue 1, 191-219.

VII. Availability of University of Utah GPS Data and Deformation Products

All Wasatch Front continuous GPS observed data are available to the interested user and to the public in near real-time via the web. The data are downloaded daily and archived in Rinex format the UNAVCO (University NAVSTAR consortium) data management center, Boulder, Colorado at http://www.unavco.org/query/pss.

University of Utah processed GPS data are posted on our website at http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html

Interpretative level research products including ground motion vectors, error analyses, etc. are available on our website http://www.mines.utah.edu/~rbsmith/RESEARCH/UUGPS.html

An important local user component of our research project provides the surveying community with our data for survey referencing with access to our data via the UNAVCO data web site above.

In addition, hourly data from the RBUT station are provided to the National Geodetic Survey and contribute to the NGS CORS on-line network that are accessible by ftp at ftp://cors.ngs.noaa.gov/coord.

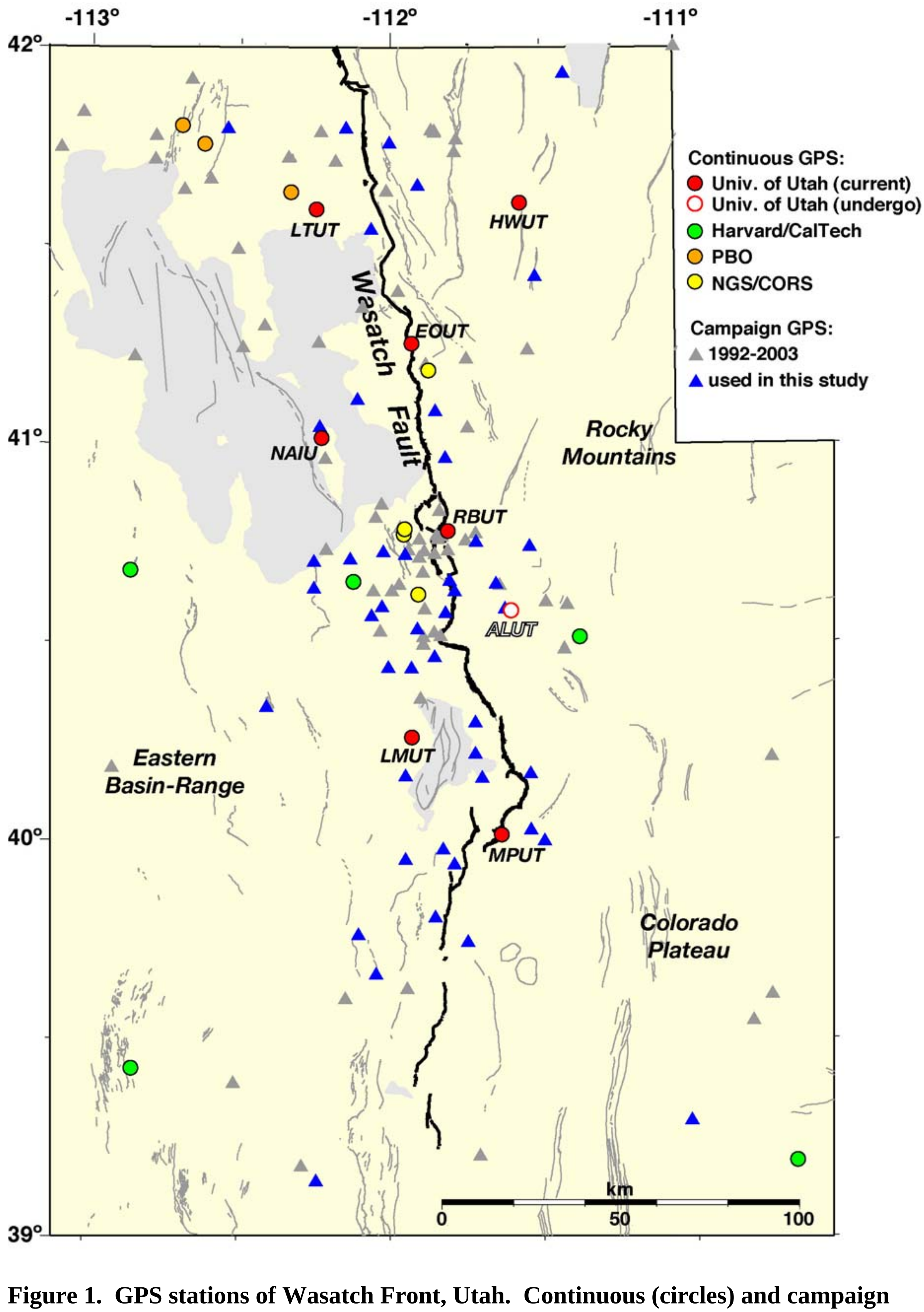

Figure 1. GPS stations of Wasatch Front, Utah. Continuous (circles) and campaign (triangles) stations are shown. Heavy black lines highlight the Wasatch fault.

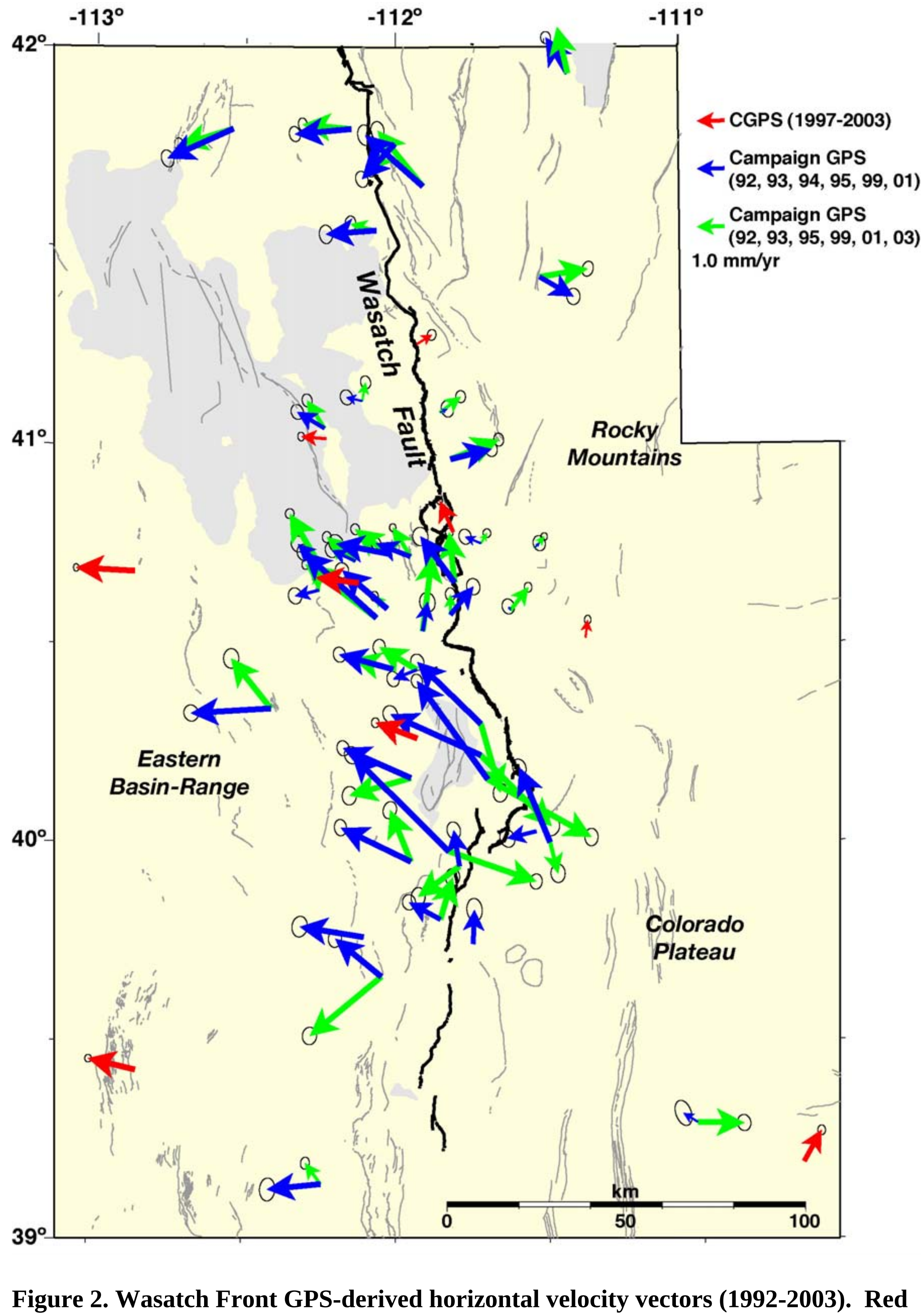

Figure 2. Wasatch Front GPS-derived horizontal velocity vectors (1992-2003). Red vectors are from continuous recording stations. Blue and green vectors are from campaign surveys.

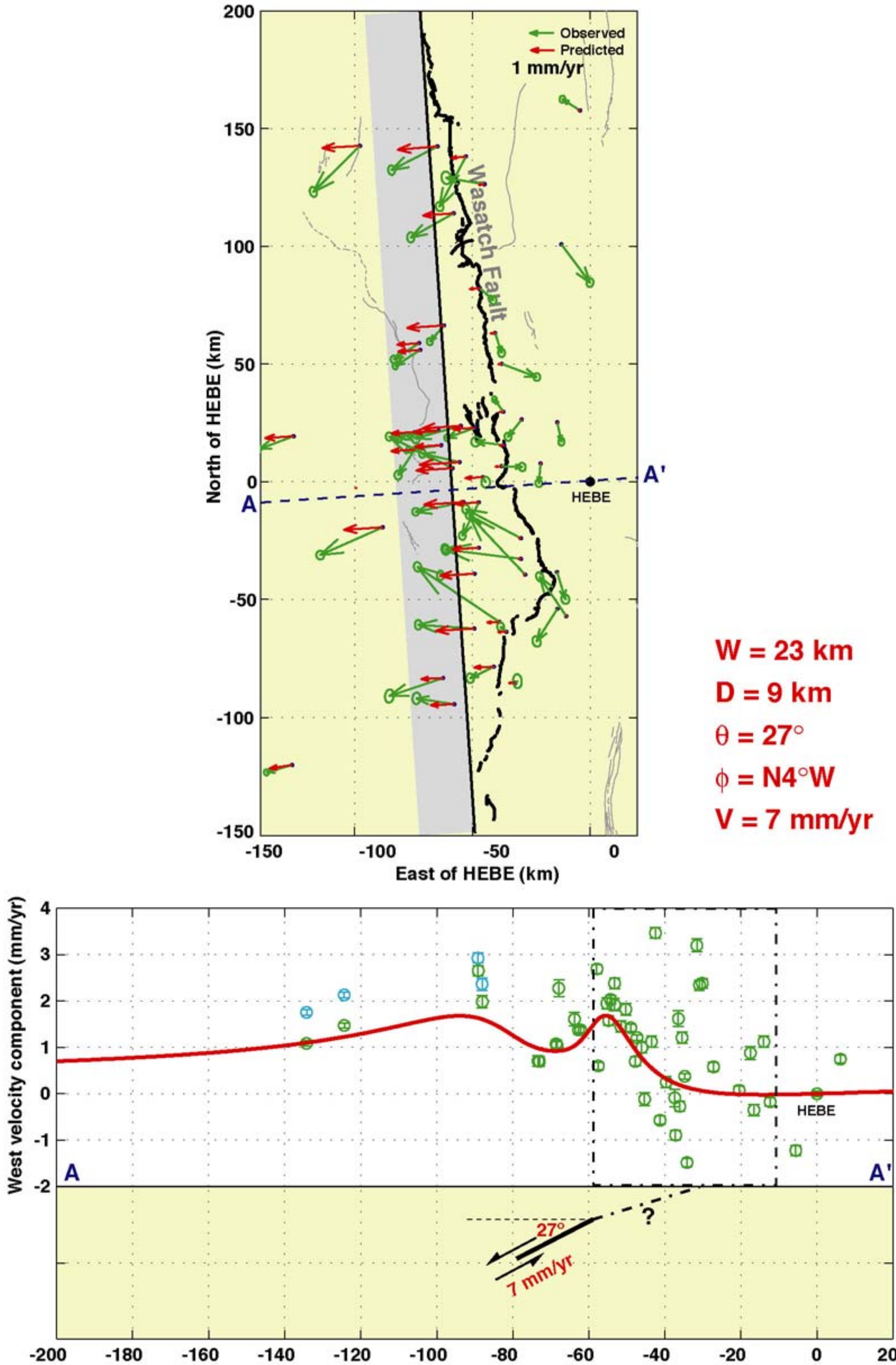

Fig. 3. Map-view (top) and vertical profile (bottom) of a horizontal motion model for a single-fault dislocation for the Wasatch fault. Parameters of the dislocation are: W=the width; D=the locking depth; θ=the dip angle, ϕ=the strike; V=the loading rate.

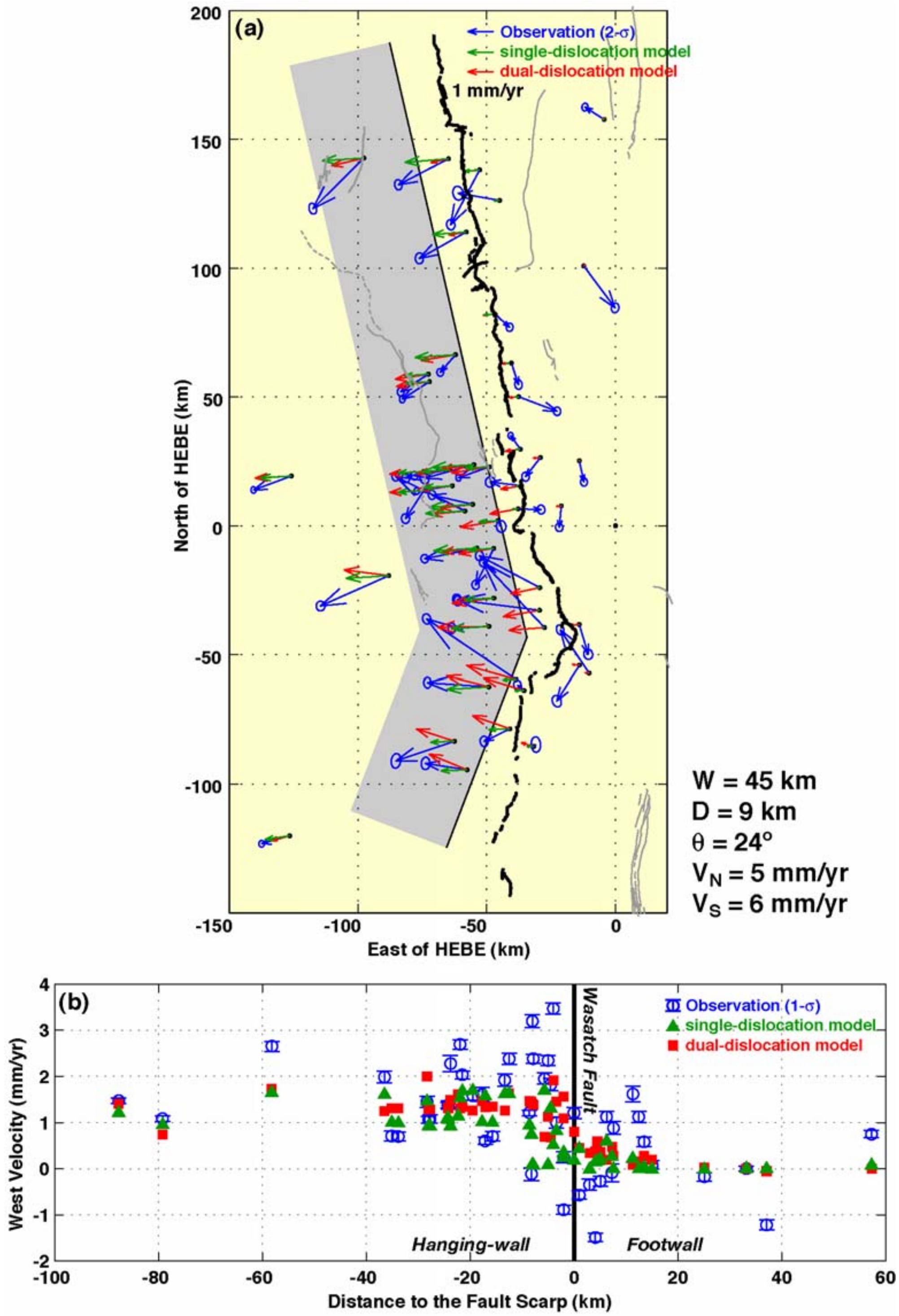

Figure 4. Laterally variable fault dislocation model that best fits the horizontal GPS velocities. (a) Predicted (red arrows) and observed (blue arrows) velocity vectors are plotted with that derived from the single-dislocation model. V_N and V_S are the loading rates of the northern and southern fault patches, respectively. (b) West velocity components are plotted with respect to the distances of the GPS sites from the mapped Wasatch fault (bold line).

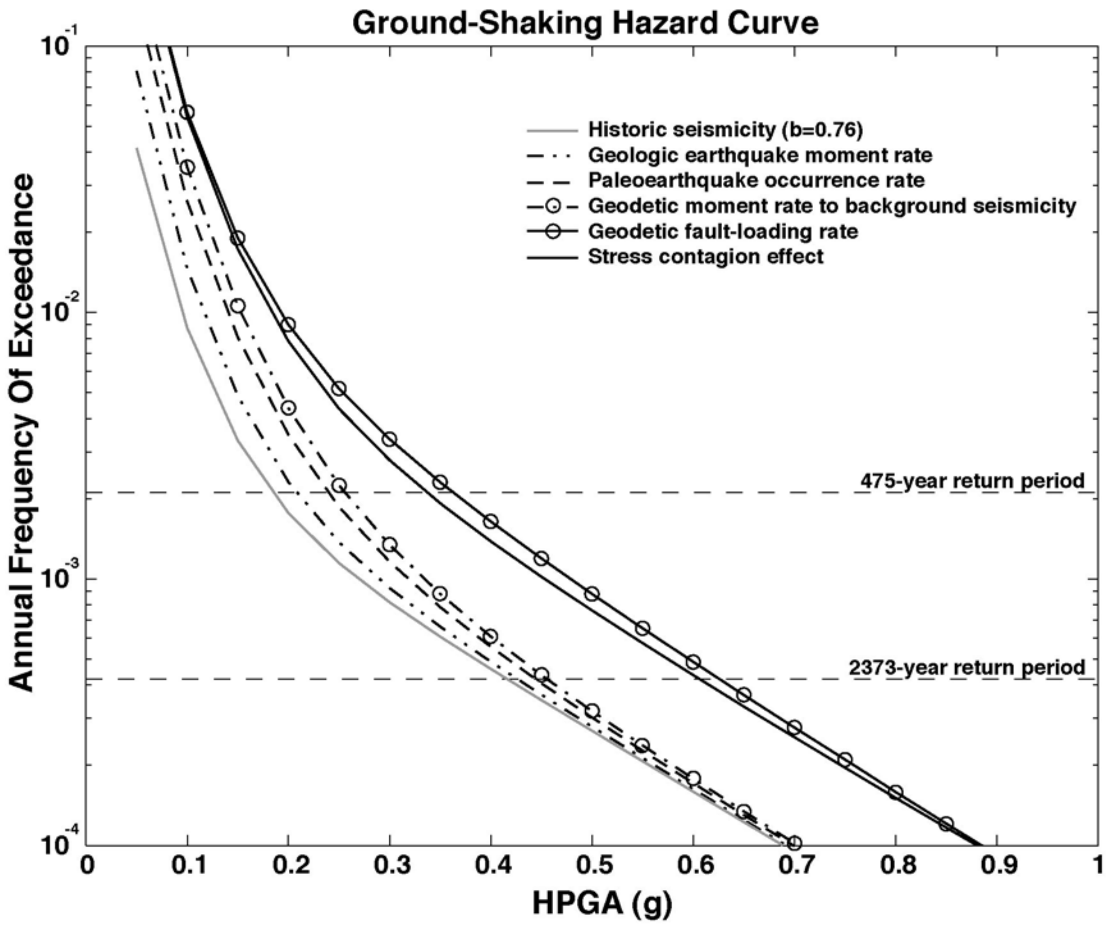

Figure 5. Earthquake ground-shaking hazard curves presenting the annual frequency of exceedance of horizontal peak ground acceleration (HPGA) for a soil site near Salt Lake City, Utah (111.9°W, 40.7°N). The HPGA attenuation for extensional regimes was used.